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STATIC LOAD MODELING FOR VOLTAGE STABILITY STUDIES WITH OPTIMAL PLACEMENT OF UPFC USING CAT SWARM OPTIMIZATION

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ABSTRACT

Voltage stability is the ability of a power system to maintain steady voltages at all buses in the system under normal operating conditions, and after being subjected to a disturbance. If the bus does not maintain the steady state value it is called as the voltage instability that may result in the form of a progressive fall or rise of voltages at those buses. Power System Load modeling is a technique used to model the power system and essential for voltage stability studies. In this paper, we are trying to analyze modeling parameters of various loads for voltage stability studies. We are performing static load modeling study. The accuracy and correctness of the results are directly related to the load models used in this analysis. The method is analyzed using continuation power flow routine. FACTS technology with a combination of Cat Swarm Optimization heuristic approach is applied to give a solution for the problem of instability due to various load models. The effectiveness of the proposed method is demonstrated through quantitative studies on standard IEEE 14 bus system.

KEYWORDS: CPF, Load Modeling, UPFC, CSO

INTRODUCTION

During the system disturbances and their impacts on other power system elements, the system stability is imperiled and the probability of moving to the global instability increases. This will usually make a power system to break up in the isolated sub-systems known as islands and then a complete blackout results unless some precautions are considered. Voltage Stability also termed as Load Stability is one of the concerns in power systems which are heavily loaded, faulted or having a shortage of reactive power [8, 10]. The problem of voltage stability concerns the whole power system, although it usually has a large involvement in one critical area of the power system. Example of the recent massive black out of India’s power grid was the worst in the decade, three out of the five regional power grids collapsed leaving about 670 million people powerless making July 2012 as the largest blackout month in history. First, the Northern Region Grid collapsed at about 2.35 am on 30th July, 2012 due to increased load and gird disturbance leaving nine states of Northern India powerless including Delhi, the capital of India. Nearly 350 million people suffered due to this power outage which resulted for about a day.

Restoration work followed with major networks of Rails, Airports, Metro and other important areas being restored under the direction of CEO, POSOCO and POWER Grid’s Chairman & Managing Director as stated by Power Grid Corporation of India. But, within 24 hours of restoration work, again the Northern region grid collapsed for the second time on 31, July 2012 at around 1pm local time on Tuesday. This time the sudden power outage resulted in collapse of two more regional girds namely, the Eastern and the North-Eastern regional Grids which spread across 20 of India’s 28 states leaving about 620 million people affected. Half of the India’s states like Delhi, Bihar, Orissa, Punjab, Haryana, Rajasthan, Uttar Pradesh etc were facing blackout Tuesday with more problems like massive traffic jams due to failed traffic lights,

miners being trapped underground as lifts failed, metro services coming to an halt and people were left scorching in the summer heat.

Power System Load modeling [12, 13] is a technique used to model the power system and essential for stability assessments. In this paper, we are trying to analyze modeling parameter inputs to loads for voltage stability studies. We are doing static load modeling and the accuracy and correctness of the results for voltage stability are directly related to the load models used in this analysis. Different load models would greatly affect voltage stability aspect of an interconnected power system. We are using continuation power flow to analyze the effects of different load models and compare the results. To analyze the maximum loading parameter and bus voltage magnitude profile aspects, we are modeling the power system with different types of loads.

Flexible Alternating Current Transmission Systems in short FACTS controllers are used to control the variables such as voltage magnitude and phase angle at chosen bus and line impedance where a voltage collapse is observed [6, 7]. Introducing FACTS devices is the most effective way for utilities to improve the voltage profile and voltage stability margin of the system. As the size and the cost of the FACTS devices are high, an optimal location and size has to be identified before they are actually installed [3, 4].

PROBLEM STATEMENT

Accurate modeling of loads continues to be a difficult task due to several factors, for example, lack of precise information on the composition of the load, changing of load composition with time delay and week, seasons, weather, through time and more. Electric utility analysts and their management require evidence of the benefits of improved load representation in order to justify the effort and expense of collecting and processing load data, as well as to modify computer program load models.

The interest in load modeling has been continuously increasing in the last years, and power system load modeling has become a new research area in power systems stability. Several studies have shown the critical effect of load representation in voltage stability studies, and therefore the need of finding more accurate load models than the traditionally used ones. In this paper we are trying to test various static load models for determining the voltage stability limits of a system. FACTS controllers are employed to give a solution for instability margins.

The static load models we are testing include ZIP model or Polynomial model, Exponential Load Model, Frequency Dependent load model and Voltage Dependent load model. We are trying to improve the voltage magnitude profile, maximum loading parameter while maintaining the losses under control using FACTS controllers. A solution is given to mitigate the harmful effects of voltage instability criterion on the power system using FACTS controllers via heuristic approach namely Cat Swarm Optimization.

The objective function for the above problem is defined as follows

$$F = \{F_1, F_2, F_3\} \tag{1}$$

The functions F_1, F_2 and $F_3$are defined and used in optimization process.

$$F = \Phi_1 F_1 + \Phi_2 F_2 + \Phi_3 F_3 \tag{2}$$

In our study, the fitness function is defined as a sum of three terms with individual criteria. The first part of the objective function concerns the voltage level. It is favorable that buses voltages be as close as possible to 1 p.u. Equation (3) shows the voltage deviation in all buses.

$$F_1 = F_v = \left[\sum_{i=1}^{n_b} (V_i - 1)^2\right]^{1/2} \tag{3}$$

Where n_b is the number of buses and V_i is the voltage of bus i.

F_2-This function represents the optimal location and size of UPFC which has its dependence on F_1.This is related to having the minimum possible UPFC sizes regarding to the control of UPFC that is given by (4)

$$F_2 = F_S = \alpha \sum_{j=1}^{m} Q_j \tag{4}$$

Where 'm' is the number of UPFC and 'Q_j' is the value of UPFC's Kvar and 'α' is a weight in order that the terms in the fitness function are comparable in magnitude. Value of UPFC's Kvar considering the control strategy and UPFC's model is achieved. The maximum load ability of power system is extremely important and hence it is considered as the third part of the objective function. So, finally, the third issue in our problem is determining inverse of maximum load ability, given as follows:

$$F_3 = F_{SM} = 1/\lambda_{Critical} \tag{5}$$

Therefore, the objective function is given by the following equation.

$$F = \Phi_1 F_V + \Phi_2 F_S + \Phi_3 F_{SM} \tag{6}$$

TEST SYSTEM AND SOFTWARE USED

The testing procedures are performed on IEEE 14-bus system. The specifications of IEEE 14 bus system can be given as: the number of buses being 14, the number of Lines being 16, the generator count is 5 (including slack bus) and the number of loads being 11. Base MVA of 100 is assumed for the test case. All the analysis and testing here is performed in MATLAB/SIMULINK [1]. Figure 1 shows the IEEE 14 bus network. This test system is modeled with ZIP, Exponential Recovery, Voltage Dependant and Frequency Dependant loads.

CAT SWARM OPTIMIZATION AND FACTS

Introduction to Cat Swarm Optimization

Optimization techniques find a variety of use in many fields. The use of these techniques in power systems is playing an important role for the optimal location of FACTS devices. In the field of optimization, many algorithms were being proposed in the recent past.

To name a few, Genetic Algorithm (GA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Simulated Annealing (SA) etc. Some of these optimization algorithms were developed based on swarm intelligence. Cat Swarm Optimization in short CSO, the algorithm, is motivated from PSO and ACO. According to the literatures, PSO with weighting factor usually finds the better solution faster than the pure PSO, but according to the experimental results, Cat Swarm Optimization (CSO) presents even much better performance [5]. In Cat Swarm Optimization, we first model the behavior of cats into two sub-models, namely, seeking mode and tracing mode [2].

Seeking Mode

This sub-model is used to model the situation of the cat, which is resting, looking around and seeking the next position to move to. In seeking mode, we define four essential factors: seeking range of the selected dimension (SRD),

counts of dimension to change (CDC), and self-position considering (SPC). SMP is used to define the size of seeking memory for each cat, which indicates the points sought by the cat.

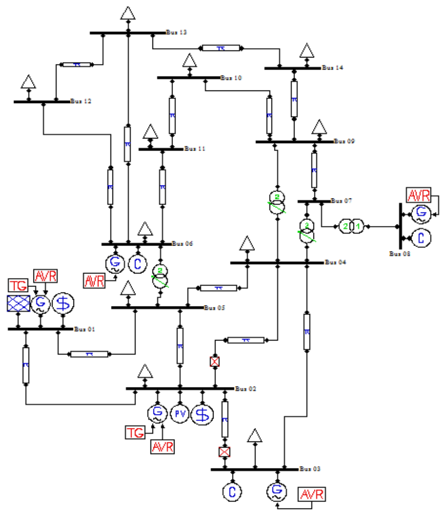

Figure 1: Standard IEEE 14-Bus System

The seeking mode can be described in 5 steps as follows:

Step1: Select the total number cats that have to be considered.

Step2: For each cat, a fixed range of velocities has to be assumed.

Step3: Calculate the fitness values (FS) of all candidate points.

Step4: Select how many cats to be available in seeking mode.

Step5: Randomly pick the cat from the total number of cats and apply in seeking mode according to the following equation.

$$P_{kn} = [(1 \pm 0.3)\, R_{and}\,(\,)]*P_k \tag{7}$$

Where, n = 1, 2, 3, 4, 5….

Where R_{and} ( ): is a random value in the range of [0, 1].

Here, 'P' is the pick-up of the cat from a random number of cats and P_k is the total number of cats available for application.

Tracing Mode

Tracing mode is the sub-model for modeling the case of the cat in tracing some targets. Once a cat goes into tracing mode, it moves according to its own velocities for every dimension. The action of tracing mode can be described in 3 steps as follows:

Step1: Update the velocities for every dimension ($V_{k,d}$) according to equation.

Step2: Check if the velocities are in the range of maximum velocity. In case the new velocity is over range, set it be equal to the limit.

Step3: Update the position of cat_k and again calculate the best fitness value. Proceed till the best fitness value is obtained and correspondingly, the cat location and the velocity.

$V_{k,d} = V_{k,d} + r_1 \cdot c_1 \cdot (P_{best,d} - P_{k,d})$, d= 1, 2,..., M (8)

Where $P_{best,d}$ is the position of the cat, which has the best fitness value.

$V_{k,d}$ is the velocity for every dimension.

$P_{k,d}$ is the position of cat_k, c_1 is a constant and r_1 is a random value in the range of [0, 1].

Algorithm for the Cat Swarm Optimization

The algorithmic flow routine for the CSO can be explained through the flow chart in figure 2.

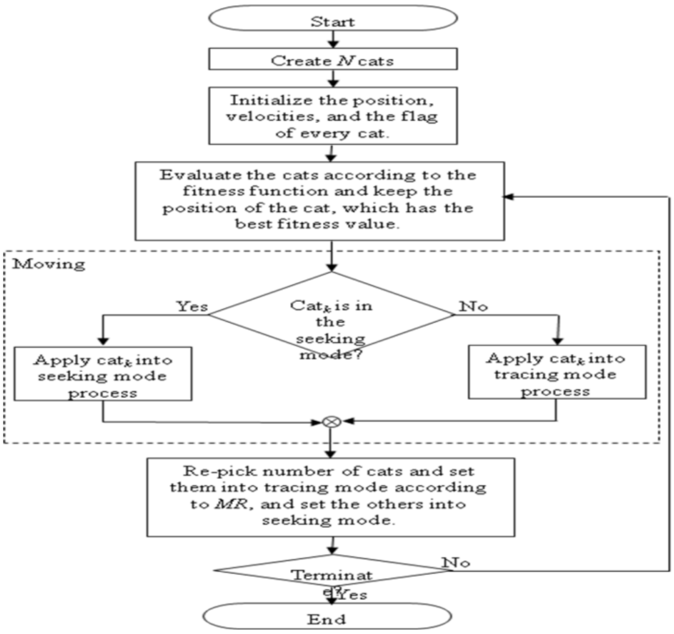

Figure 2: Flow Chart for the CSO Technique

FACTS Controllers

Flexible AC Transmission Systems (FACTS) are being used in power systems since 1970s with the objective of improving system dynamic performance. Due to the environmental, right of way, and cost problems in both bundled and unbundled power systems, many transmission lines have been forced to operate at almost their full capacities worldwide. FACTS controllers enhance the static performance viz. increased loading, congestion management, reduced system loss, economic operation, etc., and dynamic performance viz. increased stability limits, damping of power system oscillation, etc. The concept of FACTS involves a family of fast acting, high power, and electronic devices, with advanced and reliable controls. In recent years, many different FACTS controllers have been proposed, performing a wide variety of functions. Using FACTS controllers one can control the variables such as voltage magnitude and phase angle at chosen bus and line impedance where a voltage collapse is observed [9]. We are using Unified Power Flow Controller in our application.

Unified Power Flow Controller

The Unified Power Flow Controller [7] in short, UPFC is a combination of STATCOM and SSSC, sharing a common dc link as shown in figure 3. The UPFC can control both active and reactive power flow in the line. It provides independently controllable shunt reactive compensation. The UPFC is a two-port circuit (in series with a transmission line and parallel with a bus bar). The series voltage source and the shunt current source are defined as in [11]:

$V_S = (V_p+V_q)\, e^{j\varphi}=rV_k e^{j\gamma}$ (10)

$$i_{SH} = (i_p+i_q)\, e^{j\theta k} \tag{11}$$

The power equations that describe the power injection model of the UPFC are as in [11]:

$$P_{km} = b_r V_k V_m \sin(\gamma+\theta_k-\theta_m) \tag{12}$$

$$Q_{km} = b_r V_k^2 \cos\gamma - i_q V_k \tag{13}$$

$$P_{mk} = -b_r V_k V_m \sin(\gamma+\theta_k-\theta_m) \tag{14}$$

$$Q_{mk} = -b_r V_k V_m \cos(\gamma+\theta_k-\theta_m) \tag{15}$$

The POD controller can be used to modulate whatever of UPFC variables (v_p, v_q, i_q). The set of differential equations are as follows as depicted in:

$$V_p = (V_{po}+u_1V_{pod}-V_p)/T_r \tag{16}$$

$$V_q = (V_{qo}+u_2V_{pod}-V_q)/T_r \tag{17}$$

$$I_q = [K_r\,(V_{ref} + u_3V_{pod} - V_k) - i_q] \tag{18}$$

Where u_1, u_2 and u_3 are 1 if the correspondent stabilizing POD signal is enabled, 0 otherwise.

'γ' is the relative UPFC angle. V_{po} is the initial compensation voltage. V_{qo} is the initial compensation voltage. Where, V_p represents the component of the series voltage V_s that is in phase with the line current. In steady-state, the input V_{po} is set to zero so that the exchange of active power between the UPFC and the ac system only takes place when this variable is modulated by the POD controller (i.e. during transients). V_q represents the component of series voltage V_s that is in quadrature with line current. The input V_{qo} determines the value of the variable V_q in steady-state. Two control modes are implemented for this variable:

- **Constant Voltage**: the magnitude of voltage V_q is constant independently of the line current;
- **Constant Reactance**: the magnitude of the voltage V_q varies proportionally to the line current keeping constant the total impedance of the transmission line. I_q represents the component of shunt current I_{sh} which is in quadrature with the bus voltage V_k. This current keeps the bus voltage around a specified level through the regulator gain K_r.

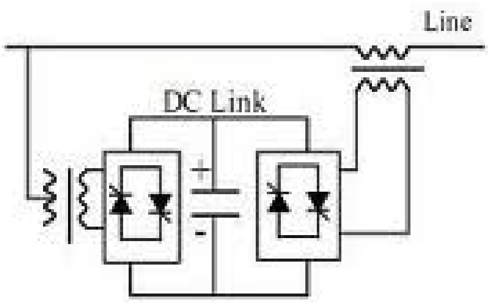

Figure 3: Structure of UPFC

IMPLEMENTATION, RESULTS AND DISCUSSIONS

We are simulating the IEEE 14 bus system with ZIP load, Voltage Dependant Load, Frequency Dependant Load and Exponential Recovery Load. The system modeled with different static loads will become instable as depicted in table 1. For this problem we are giving a solution of FACTS controller namely UPFC by using an advanced heuristic

approach namely Cat Swarm Optimization technique as discussed previously. We are incorporating three UPFC's based on the results obtained by observing the voltage magnitude profile at different buses. For installing the UPFC, the optimal size in terms of VAR ratings is determined by using Cat Swarm Optimization technique.

Table 1: Bus Voltages for Different Loads

Bus No	Zip Load	Voltage Dependant Load	Frequency Dependant Load	Exponential Recovery Load
Bus1	1.0566	1.0566	1.0572	1.057
Bus2	0.89264	0.88923	0.91956	0.91165
Bus3	0.75932	0.74094	0.76727	0.75224
Bus4	**0.73748**	**0.74086**	**0.81655**	**0.80345**
Bus5	**0.76214**	**0.76757**	**0.84161**	**0.82977**
Bus6	0.81924	0.83625	0.94378	0.93282
Bus7	0.78969	0.80221	0.91208	0.89938
Bus8	0.93511	0.94304	1.0099	1.0024
Bus9	**0.72905**	**0.74587**	**0.89255**	**0.87733**
Bus10	**0.72392**	**0.74231**	**0.89501**	**0.87959**
Bus11	0.76108	0.77959	0.91591	0.90226
Bus12	0.77332	0.79402	0.92785	0.91496
Bus13	**0.75599**	**0.77805**	**0.92092**	**0.90724**
Bus14	**0.68821**	**0.71354**	**0.88901**	**0.87218**

From table 1, we can observe, the voltages at the marked buses are less, so we considered these buses as weakest buses and FACTS devices are incorporated at these specified buses for each load to achieve the objective function for load modeling.

Table 2: Maximum Loading Parameter before and after Placing Loads

	ZIP Load		Voltage Dependent Load		Frequency Dependent Load		Exponential Recovery Load	
	With Load	Without Load	With Load	Without Load	With Load	Without Load	With Load	Without Load
Maximum Loading Parameter (λ)	2.653	2.375	2.7571	2.375	3.1718	2.375	3.14	2.375

The maximum loading parameter with and without loads are shown in table 2, we can observe that frequency dependent loads and exponential recovery loads has a considerable increase in loading parameter when compared to zip and voltage dependent loads. Even though the maximum loading parameter is increased the voltages magnitude at different buses is less and it not around 1P.U. So for this problem we are giving a solution of FACTS device.

Table 3 shows the improvement in voltage profile and maximum loading parameter for zip load when three UPFC'S are used in the location 14-13, 5-4, and 14-9 using CSO. Table 4 shows the improvement in voltage profile and maximum loading parameter for Voltage Dependant load when three UPFC'S are used in the location 14-13, 5-4, and 14-9 using CSO. From the bar graphs and PV curves shown in figures 4 and 5, we can observe that the voltage magnitude profile and the maximum loading parameter is improved by using

FACTS device when compared to the voltage magnitude profile of the base case and the objective function for Load Modeling is achieved. The same true for Voltage Dependant loads, Frequency dependant loads and Exponential Recovery Loads. The results for which are depicted from tables 4 to 6 and figures 6 to 11.

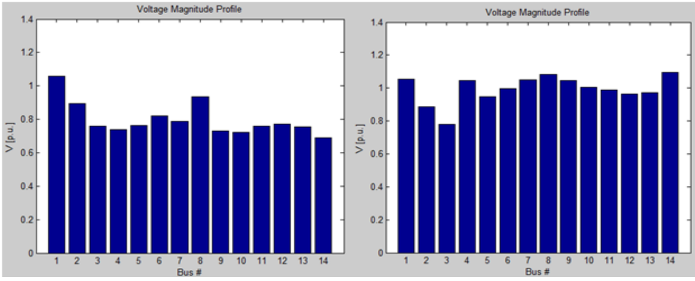

Figure 4: Voltage Magnitude Profile before and after Placement of UPFC's for ZIP Loads

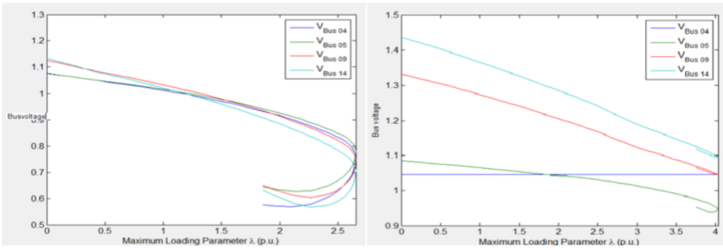

Figure 5: P-V Curves before and after Placement of UPFC's For Line ZIP Loads

Table 3: Voltage Profile before and after Placing FACTS Device for ZIP Loads

BUS. No	V(PU) (ZIP Load without UPFC)	V(PU) (ZIP Load with UPFC)
01	1.0566	1.0556
02	0.89264	0.8858
03	0.75932	0.7788
04	**0.73748**	**1.045**
05	**0.76214**	**0.9483**
06	0.81924	0.99631
07	0.78969	1.051
08	0.93511	1.0826
09	**0.72905**	**1.0451**
10	0.72392	1.0066
11	0.76108	0.9881
12	0.77332	0.96501
13	**0.75599**	**0.97184**
14	**0.68821**	**1.0955**
M L.P(λ_{max})	**2.653**	**4.0333**

Table 4: Voltage Profile before and after Placing FACTS Device for Voltage Dependant Loads

BUS. No	V(PU) (with VD Load without UPFC)	V(PU) (with VD Load with UPFC)
01	1.0566	1.0556
02	0.88923	0.88478
03	0.74094	0.77537
04	**0.74086**	**1.045**
05	**0.76757**	**0.9484**
06	0.83625	0.99748
07	0.80221	1.0516
08	0.94304	1.083
09	**0.74587**	**1.046**
10	0.74231	1.0079
11	0.77959	0.98957
12	0.79402	0.96743
13	**0.77805**	**0.97331**

Table 4: Contd.,		
14	**0.71354**	**1.0972**
M L.P(λ_{max})	**2.7571**	**4.0401**

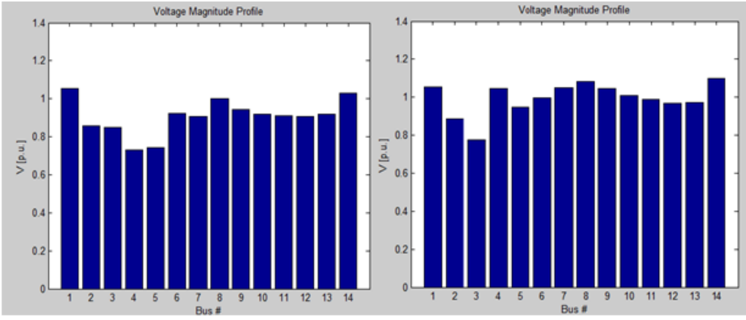

Figure 6: Voltage Magnitude Profile before and after Placement of UPFC's for Voltage Dependant Loads

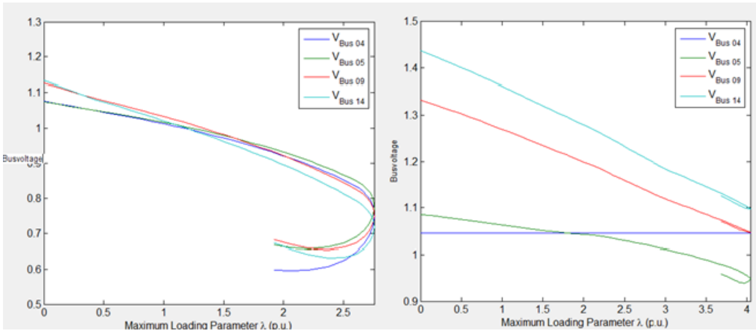

Figure 7: P-V Curves before and after Placement of UPFC's for Voltage Dependant Loads

Table 5 shows the improvement in voltage profile and maximum loading parameter for Frequency Dependant load when 3 UPFC'S are used in the location 04-05, 14-09, and 09-10 using CSO. Table 6 shows the improvement in voltage profile and maximum loading parameter for Exponential Recovery load when 3 UPFC'S are used in the location 04-05, 14-09, and 09-10 using CSO.

Table 5: Voltage Profile before and after Placing FACTS Device for Frequency Dependant Loads

BUS. No	V(PU)(with FD Load without UPFC)	V(PU)(with FD Load with UPFC)
01	1.0572	1.0588
02	0.91956	0.95597
03	0.76727	0.65951
04	**0.81655**	**1.045**
05	**0.84161**	**1.0332**
06	0.94378	0.99559
07	0.91208	1.0955
08	1.0099	1.1084
09	**0.89255**	**1.118**
10	**0.89501**	**1.045**
11	0.91591	1.0138
12	0.92785	0.96621
13	0.92092	0.98549
14	**0.88901**	1.045
M L.P(λ_{max})	**3.1718**	**4.6352**

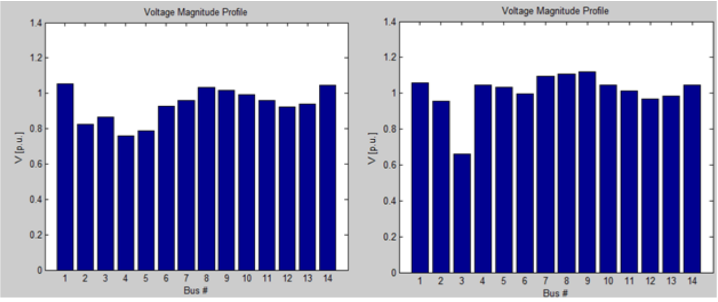

Figure 8: Voltage Magnitude Profile before and after Placement of UPFC's for Frequency Dependant Loads

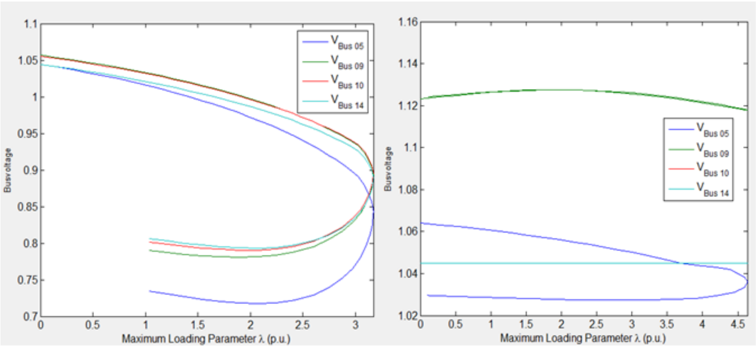

Figure 9: P-V Curves before and after Placement of UPFC's for Frequency Dependant Loads

Table 6: Voltage Profile before and after Placing FACTS Device for Exponential Recovery Loads

BUS. No	V(PU) (with ER Load without UPFC)	V(PU) (with ER Load with UPFC)
01	1.057	1.0588
02	0.91165	0.95654
03	0.75224	0.66297
04	**0.80345**	**1.045**
05	**0.82977**	**1.0332**
06	0.93282	0.99575
07	0.89938	1.0967
08	1.0024	1.1091
09	**0.87733**	**1.1207**
10	**0.87959**	**1.045**
11	0.90226	1.0134
12	0.91496	0.96541
13	0.90724	0.98542
14	**0.87218**	**1.045**
M L.P(λ_{max})	**3.14**	**4.6347**

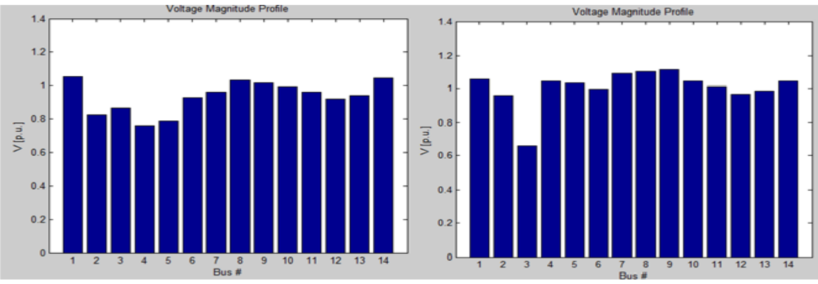

Figure 10: Voltage Magnitude Profile before and after Placement of UPFC's for Exponential Recovery Loads

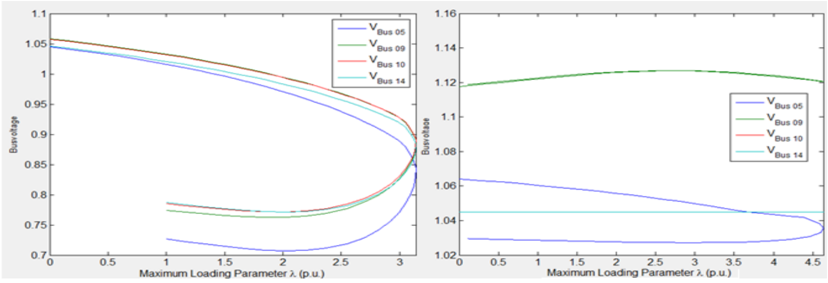

Figure 11: P-V Curves before and after Placement of UPFC's for Line Exponential Recovery Loads

CONCLUSIONS

The work presented here gives a insight and analysis of different static load models by using continuous power flow method for voltage stability analysis. The 14 bus network is modeled with different types of static loads with a performance check in terms of voltage magnitude profile and maximum loading parameter. The different load models show an impact of instability in the system for which a solution is given using FACTS controllers. A method is presented to determine the optimal location and size of FACTS controllers to enhance the power system voltage stability. This method is based on Cat Swarm Optimization (CSO). This heuristic approach was found to be easy in implementing in comparison with earlier AI techniques. It is capable of finding multiple optimal solutions to the constrained multi objective problem, giving more flexibility to make the final decision about the location of the FACTS controller. The maximum loading parameter, bus voltage profile improvement and size of device are employed as the measure of power system performance in optimization algorithm. On conclusion, we present an advanced technique to address stability issues in large power systems, which constitute variety of loads.

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